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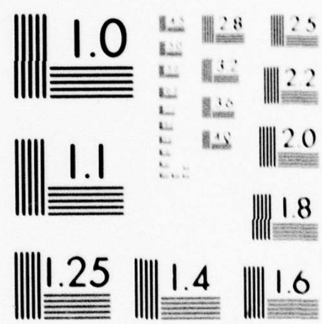

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Study of the Equatorward Edge of the Auroral Oval From Satellite Observations

B. S. DANDEKAR

9 January 1979

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FOR THE COMMANDER

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The auroral ovals in the northern and southern hemispheres observed by the optical instruments aboard the DMSP satellites are studied on a statistical basis in terms of the termporal, spatial, and magnetic activity dependence of the equatorward edge of the diffuse (continuous) aurora. In the nightside (18-08 CGT), the equatorward edges of the auroral ovals are located predominantly in the latitude range 61°-69° CGL. They show strong dependence on the levels of magnetic activity. Of the indices Kp, AE, Dst, and Q, the Q index is correlated best with the position of the equatorward edge of the diffuse aurora. ~~(over)~~

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Assuming that the auroral oval is approximately circular in a CG coordinate system, the dependence of the radius of the auroral oval on magnetic activity is determined. The radius and the center of the auroral circle changes with variation in magnetic activity. The ovals of the northern and southern hemispheres consistently show an asymmetry. On the nightside, the oval in the southern hemisphere is located about 1° closer to the equator than the oval in the northern hemisphere.

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Preface

The author is thankful to A. Lee Snyder, Lt Col, USAF for his interest in the work, and to the duty personnel from the Air Force Global Weather Center, Space Environmental Support Branch, Offutt Air Force Base, Nebraska, for scaling and providing the data from the satellites.

Study of the Equatorward Edge of the Auroral Oval From Satellite Observations

1. INTRODUCTION

The auroral zone concept of Fritz[1] and Vestine[2] was expanded to the auroral oval concept by Feldstein.[3*] The auroral oval has been studied by means of optical, ionospheric, magnetic, and precipitating particle flux observations.[4-20*] The diffuse (also called the continuous) aurora is a permanent and stable feature of the auroral oval.[21-28] The equatorward edge of the discrete auroral oval maps to the inner boundary of the earth's plasmasheet[29] and also demarcates the region between the closed and open lines of the earth's magnetic field.[30] The equatorward boundary of the auroral oval is also associated with magnetospheric parameters such as the plasmapause and plasma sheet; therefore, the dynamics of the equatorward edge of the auroral oval is important for the study of magnetospheric and ionospheric phenomena occurring at high latitudes.

This paper presents the behavior of the equatorward edge of the oval as regards its spatial and magnetic dependence. The first section describes the type

(Received for publication 8 January 1979)

1. Fritz, H., (1881) Das Polaricht, Leipzig, Germany.
2. Vestine, E.H., (1944) The geographic incidence of aurora and magnetic disturbance, Northern Hemisphere, Terr. Magn. Atmos. Elec. 49:77.

* Due to large number of references cited on this page, they will not be listed here. See References 3-30, pages 41-42.

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of data and the procedure used in the analysis, and the last section discusses the results and implications of the study.

2. DATA AND ANALYSIS

The data are collected from the satellites of the Defense Meteorological Satellite Program (DMSP). The DMSP satellites are in sun-synchronous polar orbit of 98.7° inclination, at nominal altitudes of 815-850 km. At a given time there are generally two satellites, one in the dawn-dusk meridian and the other in the noon-midnight meridian. The orbital period of each satellite is 102 min. The satellites are used basically for tropospheric weather observations and as they carry optical sensors, observations of aurora have been available. The satellites which contributed to the data in this study are listed in Table 1.

Brief descriptions of the DMSP satellite program and instrumentation have been presented by Vesely and Botzong,[31] Spangler,[32] Rogers et al.[33] and Pike.[34] Until now, observations from these satellites have been used mainly for case studies.[7, 23, 34-36] In the present study, the data covering the period from June 1972 to March 1976 are used for the statistical determination of the spatial and magnetic dependence of the equatorward edge of the auroral oval.

A single parameter, the equatorward edge of the diffuse aurora at the subsatellite track, is used in the present study. The diffuse auroral edge is determined from the auroral photos produced by the optical sensors aboard the satellites. The minimum detectable signal in the auroral pictures is 8.5×10^{-10} watts cm^{-2} $sterad^{-1}$, covering a wide spectral range of 400-1150 nm.[33] The predominant auroral features in this spectral range are [OI] 557.7 nm, [OI] 630.0 nm and

31. Vesely, C.J., and Botzong, W.B., (1974) Defense Meteorological Satellite Program, Presented at Sixth Conference of Aerospace and Aeronautical Meteorology, AWS, El Paso, Texas Chapter.

32. Spangler, M.J., (1974) What's the weather down there? Westinghouse Engineer.

33. Rogers, E.H., Nelson, D.F., and Savage, R.C., (1974) Auroral photography from a satellite, Science 183:951.

34. Pike, C.P., (1975) Defense Meteorological Satellite Program, Auroral-Ionospheric Interpretation Guide, AFCRL-TR-75-0191, Air Force Surveys in Geophysics, 306.

35. Pike, C.P., Dandekar, B.S., Meng, C.-I., and Akasofu, S.-I., (1976) A correlation study relating DMSP satellite observations of the aurora to the Bz component of the IMF, EOS transactions, Am. Geophys. Union 57:313.

36. Dandekar, B.S., and Pike, C.P., (1977) Dayside auroral gap, EOS (Trans. AGU) 58:479.

Table 1. DMSP Satellites Which Contributed Data to the Present Study

Satellite No.	Orbit	Period of Auroral Observations
5528	Noon-midnight	Jun 72 - Feb 74
6530	Dawn-dusk	Nov 72 - Jun 73
7529	Dawn-dusk	Aug 73 - Dec 76
8531	Noon-midnight	Mar 74 - May 76
9532	Dawn-dusk	Aug 74 - Nov 74
10533	Dawn-dusk	May 75 -
DMSP - Defense Meteorological Satellite Program - formerly known as Data Acquisition and Processing Program (DAPP).		

636.4 nm, N_2 first positive, N_2^+ Meinel band systems and the hydrogen line emissions.[37] Due to the response characteristics of the sensor, the main emissions contributing to the brightness in the photos from the satellites are the N_2 first positive, and N_2^+ Meinel bands. Different emissions contribute to different sectors of the auroral oval.[21, 38-44.] In the auroral oval, optical emissions are produced mainly by precipitating particles such as the electrons and protons. In the noon sector of the oval, the major source contributing to the particle precipitation is the region between the magnetopause and the shockfront; that is, the magnetosheath.

37. Berkey, F.T., and Kamide, Y., (1976) On the distribution of global auroras during intervals of magnetospheric quiet, J. Geophys. Res. 81:4701.

38. Vallance, Jones A., (1969) Spectroscopic morphology of aurora, Ann. IQSY 4:349.

39. Eather, R.H., (1969) Latitudinal distribution of auroral and airglow emissions: the "soft" auroral zone, J. Geophys. Res. 74:153.

40. Eather, R.H., and Mende, S.B., (1971) Airborne observations of auroral precipitation patterns, J. Geophys. Res. 76:1746.

41. Eather, R.H., and Mende, S.B., (1972) Systematics in auroral energy spectra, J. Geophys. Res. 77:660.

42. Heikkila, W.J., Winningham, J.D., Eather, R.H., and Akasofu, S. -I., (1972) Auroral emissions and particle precipitation in the noon sector, J. Geophys. Res. 77:4100.

43. Deehr, C.S., Egeland, A., Aarsnes, K., Amundsen, R., Lindalen, H.R., Soraas, F., Dalziel, R., Smith, P.A., Thomas, G.R., Stanning, P., Borg, H., Gustafsson, G., Holmgren, L.A., Redler, W., Raitt, J. (1973) Particle and auroral observations from ESROI/AURORAE satellite, J. Atmos. Terr. Phys. 35:1979.

44. Mende, S.B., and Eather, R.H., (1976) Monochromatic all-sky observations and auroral precipitation patterns, J. Geophys. Res. 81:3771.

Precipitated particles from the magnetotail of the plasma sheet are known to be responsible for the nightside of the auroral oval.[11]

No effort is made in this study to separate the various factors in determining the equatorward edge of the diffuse aurora of the oval. The data were scaled from the photographs on a routine basis by the personnel from the Air Force Global Weather Central, Offutt Air Force Base, Nebraska, according to the procedures recommended by Cohen.[45] The number of orbits used for the northern and southern hemisphere in this study are summarized in Table 2.

These data were made available by the Air Weather Service in the form of punched card decks. There are gaps in the data, and they can be accounted for in different ways. One of the most likely reasons was the strong contamination due to background illuminations under varying conditions of solar and lunar shadow heights and clouds. Another possibility was the malfunction of one of the two recorders, that resulted in an inability to collect and record data during the transmission of stored data by the working recorder to a ground station. An additional cause could be attributed to the mode of operation of the satellites or the decision by the operators to record or neglect the data. Another limitation was due to the fact that the data were scaled routinely only in the night sector of the auroral oval, although data were also recorded in the day sector.

The auxiliary data for the magnetic activity were provided by World Data Center A, Boulder, Colorado. Kp, AE, Dst, and Q indices were used for studying the dependence of the equatorward edge on the magnetic activity. AE data were only available for the calendar years 1972-1974.

Table 2. Number of Observations for Equatorward Edge of the Diffuse Aurora

Year		1972	1973	1974	1975	1976	TOTAL
Hemi-	North	1211	981	1496	1357	638	5683
sphere	South	459	441	975	826	---	2701
TOTAL		1670	1422	2471	2183	638	8384

45. Cohen, N.L., (1975) Gridding Procedures for DMSP Transparencies, Defense Meteorological Satellite Program, Auroral Ionospheric Interpretation Guide, Ed. C.P. Pike, Air Force Surveys in Geophysics No. 306, AFCRL-TR-75-0191, Chap. 4. AD A013165

The data were separated into two groups, one for the northern hemisphere and the other for the southern hemisphere. Auroral photographs from the satellite are recorded in the geographic system of coordinates. As auroral phenomena exhibit geomagnetic control, the data are converted to the geomagnetic system of coordinates of Hakura.[46] The corrected geomagnetic coordinates of Hakura[46] refer to the ground level, whereas the auroras under study originate in the altitude range of 100 to 150 km. The use of ground CG coordinate system of Hakura[46] to auroras, around altitude of 100 km, introduces a systematic error in the location of the aurora. In this case, the position of the aurora would shift 0.2° towards the geomagnetic pole. In our study this systematic error has been neglected.

The limit of resolution in the auroral photograph results in an error of less than 0.2° in the determination of the latitude of the equatorward edge of the diffuse aurora. The temporal and spatial dependence of the equatorward edge is determined from the frequency distribution of the data over the intervals of latitude and longitude.

The main focus in the analysis is towards the study of the magnetic dependence of the equatorward edge of the diffuse aurora on various indices of magnetic activity. The magnetic dependence is studied in terms of the magnetic activity indices Kp, AE, Q, and Dst. The limitations of these indices have been discussed by Rostoker.[47] Data for magnetic activity are divided in appropriate intervals. For each interval of magnetic activity, an average position of the geomagnetic latitude of the equatorward edge of diffuse aurora and its standard deviation is determined from the observations.

The comparison of the dependence of the equatorward edge of diffuse aurora on various indices of magnetic activity is achieved by the following:

1. In studying the general dependence of the latitude of the equatorward edge of diffuse aurora on magnetic activity, the corrected geomagnetic time (CGT) dependence of latitude of diffuse aurora is first neglected. The least-square straight-line fit is determined between the given index of magnetic activity and the latitude from all the data of each hemisphere. For the sake of presentation, average values of the latitude of diffuse aurora and their standard deviation over each interval of magnetic activity are shown along with least-square straight-line fit.

2. The following procedure was used to compare the results for different indices of magnetic activity. For a given index of magnetic activity, the average and the standard deviation of the index were determined only for the observations

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46. Hakura, Y., (1965) Tables and maps of geomagnetic coordinates by higher order spherical harmonic terms, Rep. Ionos. Space Res. Japan 19:121.

47. Rostoker, G., (1972) Geomagnetic indices, Rev. Geophys. Space Phys. 10:935.

of the diffuse aurora. The upper and lower limits for magnetic activity were set as the average value plus the standard deviation, and the average value minus the standard deviation, respectively. From the least-square straight-line fit between latitude of the aurora and the given index of magnetic activity the latitude ranges were found at these upper and lower limits of the magnetic activity. These latitude ranges were compared for the magnetic activity indices Kp, Q, AE, and Dst.

3. As the auroral oval exhibits a dependence on CGT, a least-square circle is fitted to all the data from each hemisphere. The parameters used in the least-square circle fit are the CG latitude and the CG time of the equatorward edge of the diffuse aurora, and the value of the index for the magnetic activity at the time of observation. As the indices Kp and Q are found most suitable in Step 1, the least-square circle fit is carried out for these indices only.

4. For simplifying and facilitating comparison amongst the results obtained for the latitude dependence on various indices of magnetic activity, only first order least-square fits are used. The corresponding curves for the data of the northern hemisphere are presented by continuous curves in the figures. Dashed curves are used for showing the data from the southern hemisphere.

3. RESULTS

The determination of the equatorward edge of the diffuse aurora from the satellite picture depends on several factors such as the threshold sensitivity of the instruments, ground albedo, shadow heights due to solar and lunar elevations, and cloud coverage. Further, the auroras were scaled only from observations during the movement of the satellite from the pole towards the equator. In spite of such limitations and the loss of data during periods of instrumental malfunctions, useful data, listed in Table 2., provides information for over 15 percent of the satellite tracks in the region of the auroral ovals on a global basis. In the discussion, because of the nature of the data base, the results apply only to the night sector of the auroral oval.

In this study, the range of geomagnetic latitude was arbitrarily limited to $55° - 77°$, with the assumption that data beyond this range is probably due to errors in reading the equatorial edge of the diffuse aurora from the auroral photographs. This process, in addition to the removal of data points with large standard error and/or small sample for the intervals (discussed in analysis section), eliminated less than 1 percent of the observations from those listed in Table 2.

4. TEMPORAL DEPENDENCE

A distribution of observations from the satellites, available for analysis, as a function of CGT is shown in Figure 1. Some of the factors affecting the distribution have already been discussed above. Under the circumstances, observations can provide useful information in the 16-08 hour interval of CGT, and obviously it is not possible to use this data-base for determining the temporal dependence, or the behavior of the equatorward edge of the diffuse aurora in the day sector. It is emphasized that the single and double peaks in the distribution of observations in the southern and northern hemispheres, respectively, are due to modes of observations from the satellites, and to the data scaling procedures, and need not have any significance as the occurrence frequencies of the diffuse auroras with the local time.

5. SPATIAL AND LATITUDINAL DEPENDENCE

The dependence of the distribution of observations of the diffuse aurora on the geomagnetic latitude is presented in Figure 2 for the northern and southern hemispheres. The distribution peaks around 64° in the northern hemisphere and around 63° in the southern hemisphere. One standard deviation spans the latitude range 62°-68° in the northern hemisphere, and 61°-68° in the southern hemisphere.

At this stage, it is noted that there is a difference of more than a degree of latitude in the peaks of the frequency of occurrence between the northern and the southern hemispheres. The boundary in the southern hemisphere is more equatorwards than the boundary in the northern hemisphere. This difference is observed in all the analyses that follow. The possible explanations are (a) asymmetry of the earth's magnetic field between the northern and the southern hemispheres, and (b) the inadequacy of the geomagnetic model used in the conversion of geographic to geomagnetic coordinates.

In comparing the latitude dependence presented here with that from prior work, it should be noted that the prior observations were from ground-based all-sky camera systems (ASCA). The minimum detectable signal from the ASCA is about 1 kR for [OI] 557.7 nm line emission. Discrete arcs are dominant auroral features observed by the ground-based cameras. The data from the ASCA covers a wide range of solar activity, from solar maximum in the IGY period to the solar minimum in the IQSY period, and most of the observations are for the local midnight periods.

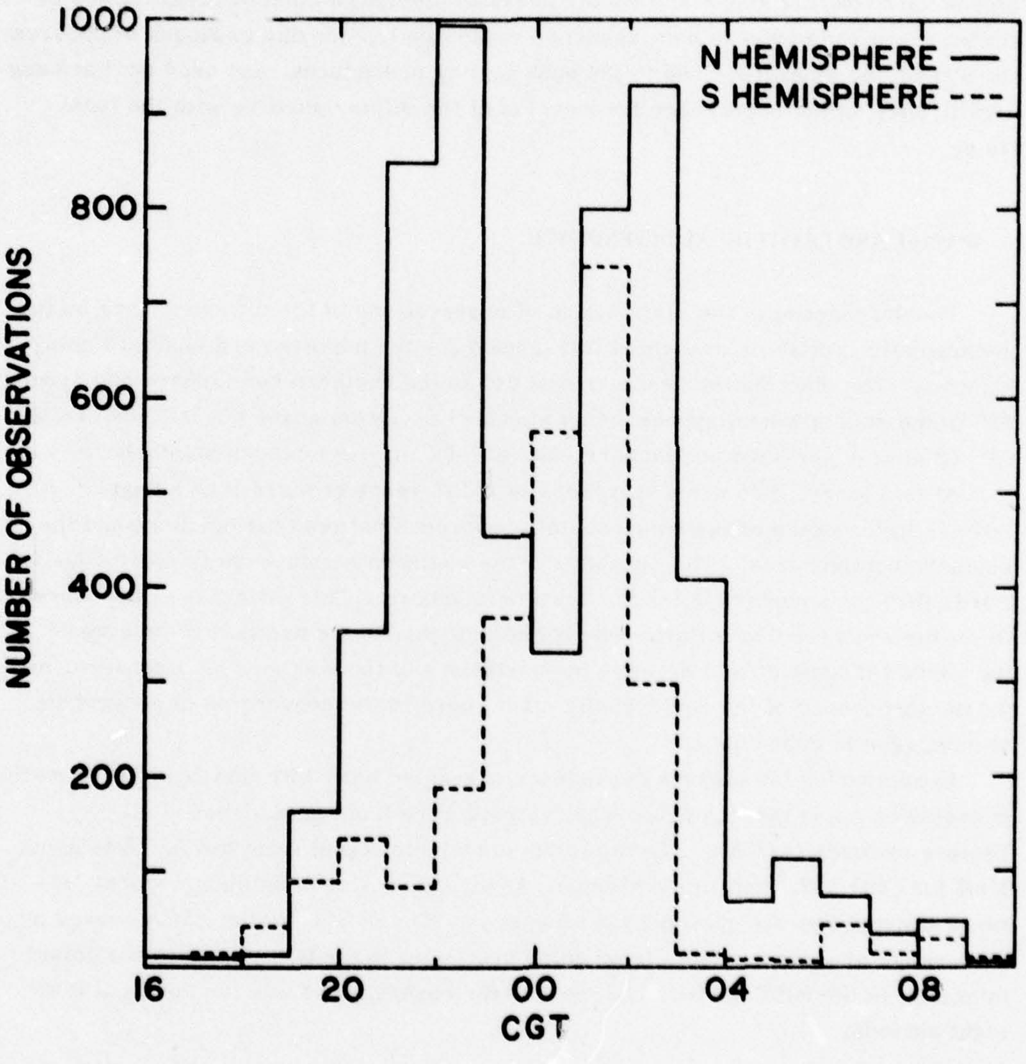

Figure 1. Distribution of Observations Available for the Equatorward Edge of Diffuse Aurora as a Function of Corrected Geomagnetic Time (CGT)

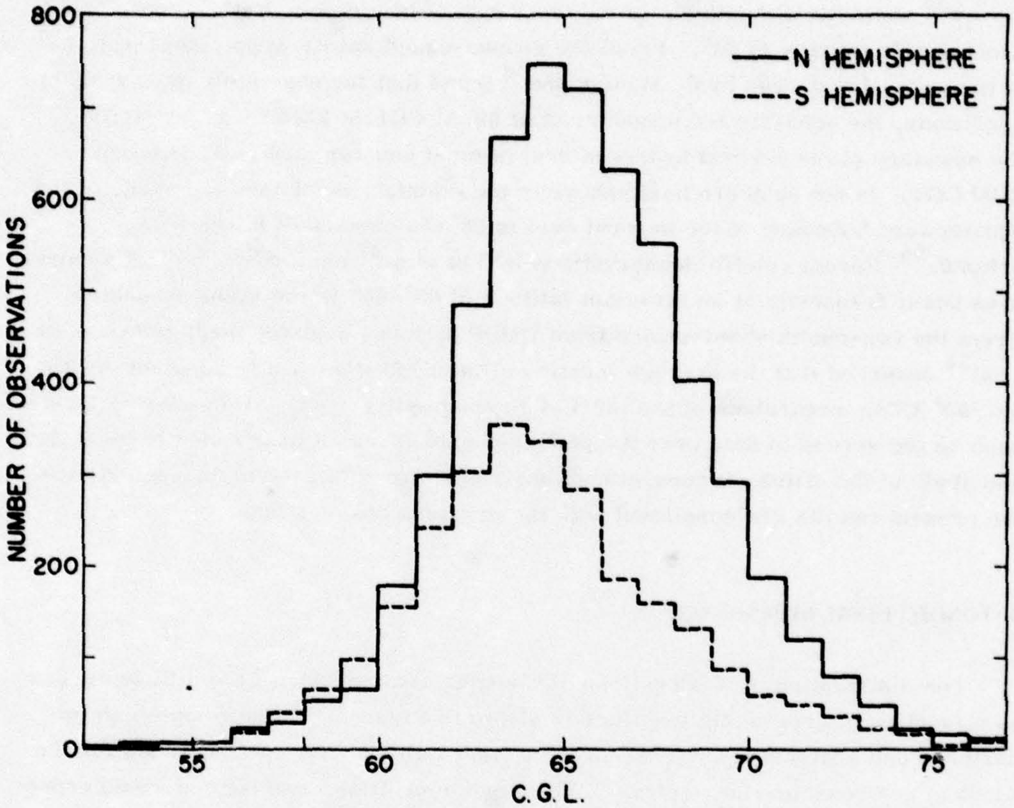

Figure 2. Observed Distribution of Diffuse Aurora vs. Corrected Geomagnetic Latitude (CGL)

Feldstein and Starkov[48] observed the equatorward edge at 66° -67° CGL for 0≤Kp≤1 during the IGY and IQSY for midnight hours. During high-magnetic activity Kp=5, the equatorward edge was at 58° during the IGY period, and at 63° during the IQSY period, showing a solar cycle dependence. Stringer et al[49] observed

48. Feldstein, Y.I., and Starkov, G.V., (1967) Dynamics of auroral belt and polar geomagnetic disturbances, Planet. Space Sci. 15:209.

49. Stringer, W. J., Belon, A.E., and Akasofu, S.-I., (1965) The latitude of auroral activity during periods of zero and very weak magnetic disturbance, J. Atmos. Terr. Phys. 27:1039.

the peak occurrence around 69° for Kp=1. During the IGY and the IQSY periods, the equatorward edge in the Alaskan sector was at 66° dipole latitude.[50-52] Isayev[53] observed a maximum in the frequency of occurrence of the aurora at the geomagnetic latitude of 68°. From the ground-based spectroscopic observations of the auroral hydrogen oval, Montbriand[54] found that for absolutely quiet magnetic conditions, the equatorward boundary is at 68.5° CGL at 2315 CGT. At $4 < Kp < 5$, the boundary of the auroral hydrogen oval is most equatorward at 63° CGL at 2100 CGT. In the southern hemisphere in the midnight meridian, the range of the equatorward boundary of the auroral oval is 58°-66° invariant latitude for $5 \geq Kp \geq 0$.[55] Recent satellite observations by Lui et al[27] show that the quiet auroral arcs occur frequently at an invariant latitude of 65°-66° in the midnight sector. From the two-month observations from DMSP pictures over the south pole Nagata et al[56] observed that the average location of the diffuse aurora is constant around 68°-69° CGL, regardless of the level of geomagnetic activity. Considering factors such as the spread of data over the period of four years, a wide range of local time, and study of the diffuse aurora without any restriction of spectral characteristics, the present results are consistent with the previous observations.

6. LONGITUDINAL DEPENDENCE

The distribution of observations of the equatorward edge of the diffuse aurora as a function of geographic longitude is shown in Figure 3 for data from both the northern and southern hemispheres. The figure also shows the longitudes for the Alaskan and Scandinavian sectors. With a polar orbiting satellite one would expect a reasonably uniform coverage of all longitudes around the earth. Each satellite carries two tape recorders. While one tape recorder transmits data to the ground

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50. Davis, T.N., (1962) The morphology of the auroral displays of 1957-1958, J. Geophys. Res. 67:75.
51. Stringer, W.J., and Belon, A.E., (1967a) The statistical auroral zone during IQSY and its relationship to magnetic activity, J. Geophys. Res. 72:245.
52. Stringer, W.J., and Belon, A.E., (1967b) The morphology of the IQSY auroral oval, J. Geophys. Res. 72:4423.
53. Isayev, S.I., (1962) The geographical distribution of auroras and the earth's radiation belts, Geomagn. Aeron. (Eng. ed.) 2:552.
54. Montbriand, L.E., (1976) The oval of hydrogen emissions, Canad. J. Phys. 54:2310.
55. Bond, F.R., and Thomas, I.L., (1971) The southern auroral oval, Aust. J. Phys. 24:97.
56. Nagata, T., Hirasawa, T., and Ayukawa, M., (1976) Auroral oval and polar substorms observed by a satellite and ground based observations in Antarctica, National Institute of Polar Research: Memoirs, Special Issue 6:25.

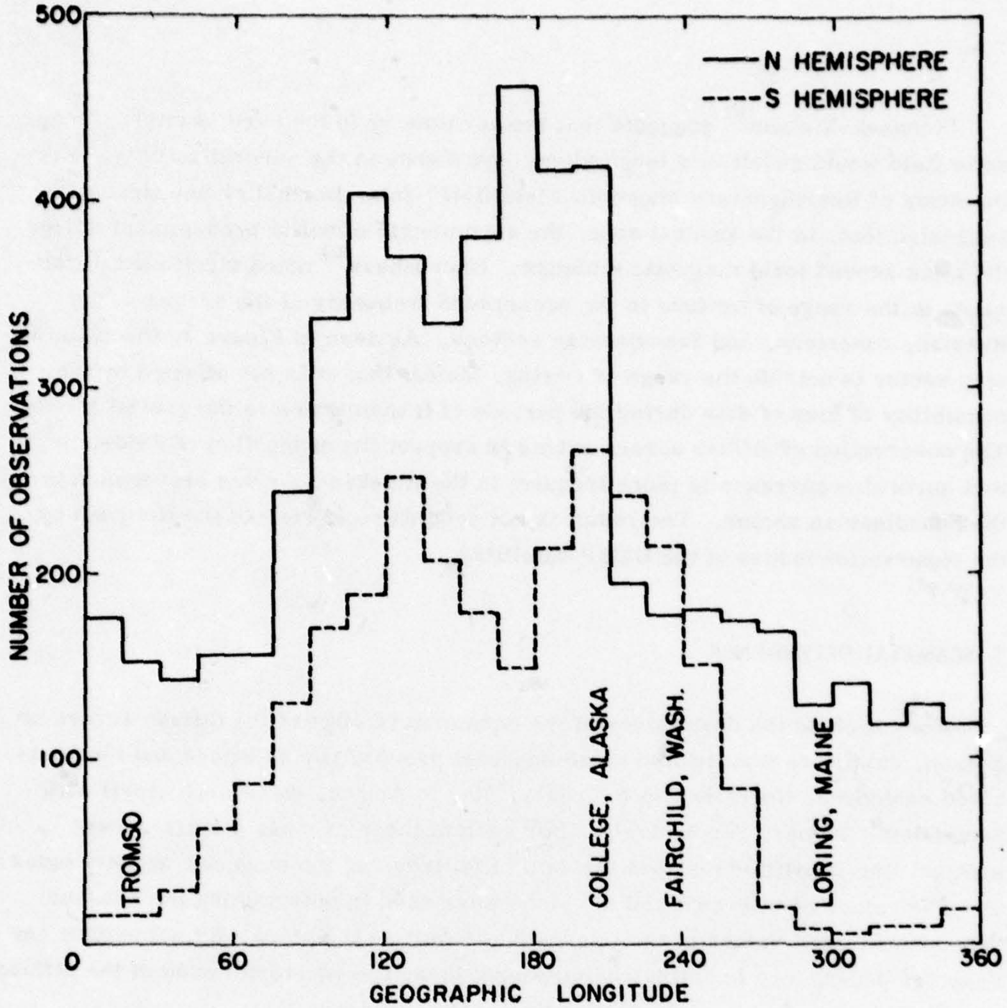


Figure 3. Observed Distribution of Diffuse Aurora vs. Geographic Longitude

station, the other records the data during that interval; however, failure of one of the tape recorders would create gaps in the auroral observations. Data are transmitted to two ground stations located on the eastern and the western border of the U.S. (Loring, Maine and Fairchild, Washington). At the satellite altitude of 835 km, the lack of storing data during the transmission period would result in a gap in data with longitude range of 40° on either side of the ground station. The longitudes for the ground receiving stations are also shown in the figure. In the data set available for this study, observations do not have a uniform coverage in longitude. The figure shows that the data basically cover the geographic longitude range 75° -255°E in the northern hemisphere, and 105° -240°E in the southern hemisphere.

Stenbaek-Nielsen[57] suggests that the asymmetry in the earth's internal magnetic field would result in a longitudinal dependence in the auroral activity. From the study of Interplanetary Magnetic Field (IMF) data, Berthelier and Guerin[58] suggested that, in the auroral zone, the asymmetric effect is predominant during the night around local magnetic midnight. Khorosheva[59] noted significant differences in the range of latitude in the occurrence frequency of the aurora in the Russian, American, and Scandinavian sectors. As seen in Figure 3, the Scandinavian sector is outside the range of Loring, Maine; thus it is not affected by the possibility of loss of data during the periods of transmission to the ground station. The observation of diffuse aurora seems to support the suggestion of Feldstein[11] that auroral occurrence is more frequent in the Alaskan-Siberian sector than in the Scandinavian sector. The result is not conclusive in view of the limit set by the observation modes of the DMSP satellites.

7. SEASONAL DEPENDENCE

For checking the dependence of the equatorward edge of the diffuse aurora on season, data were divided into three seasonal groups, two solstices and the combined equinoxes, November to February, May to August, and March-April with September-October, respectively. For each of these groups, a least-square straight line was fitted between the data of latitude and the magnetic activity index Q. The values of intercept and the slope were used in determining the seasonal dependence. The values of the intercept, as well as the slope, did not exhibit any seasonal dependence for either hemisphere; thus, the equatorial edge of the diffuse aurora does not show any significant seasonal dependence.

8. DEPENDENCE ON THE MAGNETIC ACTIVITY

First, the general dependence of the equatorward edge of the auroral oval (determined from the diffuse aurora) on the magnetic activity will be considered. For this purpose, data of geomagnetic latitudes of equatorward edge of diffuse aurora are divided in corresponding intervals of magnetic activity, irrespective of

57. Stenbaek-Nielsen, H. C., (1974) Indications of a longitudinal component in auroral phenomena, J. Geophys. Res. 78:2521.

58. Berthelier, A., and Guerin, C., (1973) Influence of the polarity of the interplanetary magnetic field on magnetic activity at high latitudes, Space Res. XIII:601.

59. Khorosheva, O.V., (1967) Spatial temporal propagation of aurora, Aurora and Airglow (USSR) 16:3.

their wide coverage of longitude and CGT. The corrected geomagnetic latitude data are correlated with four indices of magnetic activity, Kp, Q, AE, and Dst. Except for the index Q, all other indices are determined on a global basis. The Q index data are available only from a single station, Sodankyla, Finland (67.5°N, 26.6°E geographic) in the northern hemisphere. A common shortcoming of these magnetic indices is that few stations from the southern hemisphere contribute to the determination of their values. These indices are obtained principally from observatories in the northern hemisphere and have been used to study auroral data from both hemispheres. Mayaud[60] has already observed that the magnetic activity index Kp in the northern hemisphere is about 10 percent larger than that in the southern hemisphere. In this statistical study it is not possible to determine how much the results would be affected by such a small difference in the levels of magnetic activity between those of the northern and the southern hemispheres.

In Figure 4, sections A, B, C, and D present the northern hemisphere results of the dependence of the equatorward edge of the oval on the magnetic activity in terms of indices Kp, Q, AE and Dst, respectively. In each section, the solid circles show the average value of the latitude over the given interval of magnetic activity. The vertical lines show the standard deviation over the interval. The continuous line shows the least-square straight line fit to all the data. The empirical relation is presented at the top of each section. In Figure 5, sections A, B, C, and D, the corresponding results are presented for the southern hemisphere. The results in Figures 4C and 5C show that dependence on AE could be presented better by fitting two segments of curves, one for interval AE ≤400 and the other for interval AE >400 . Therefore, two segments of least-square straight-lines are used for the correlation with the AE index.

The feature common to all the sections is the equatorward movement of the edge of the oval with increase in magnetic activity. For a given magnetic activity, the oval in the northern hemisphere is about 1° poleward of the corresponding point in the southern hemisphere.

The results of straight-line fits between equatorward edge of the diffuse aurora and different indices of magnetic activity were compared in the following way. For each index of magnetic activity used with the auroral data, an average value and the standard deviation were determined. The lower and upper ranges for a given index of magnetic activity were set, respectively, as average value minus the standard deviation, and the average value plus the standard deviation. At these lower and upper ranges of magnetic activity, the corresponding positions

60. Mayaud, P.N., (1970) Sur quelques propriété's de l'activité, magnétique, déduites de l'analyse d'une séries de neuf anées des indices Kn, Ks et Km, Ann. Geophys. 26:109.

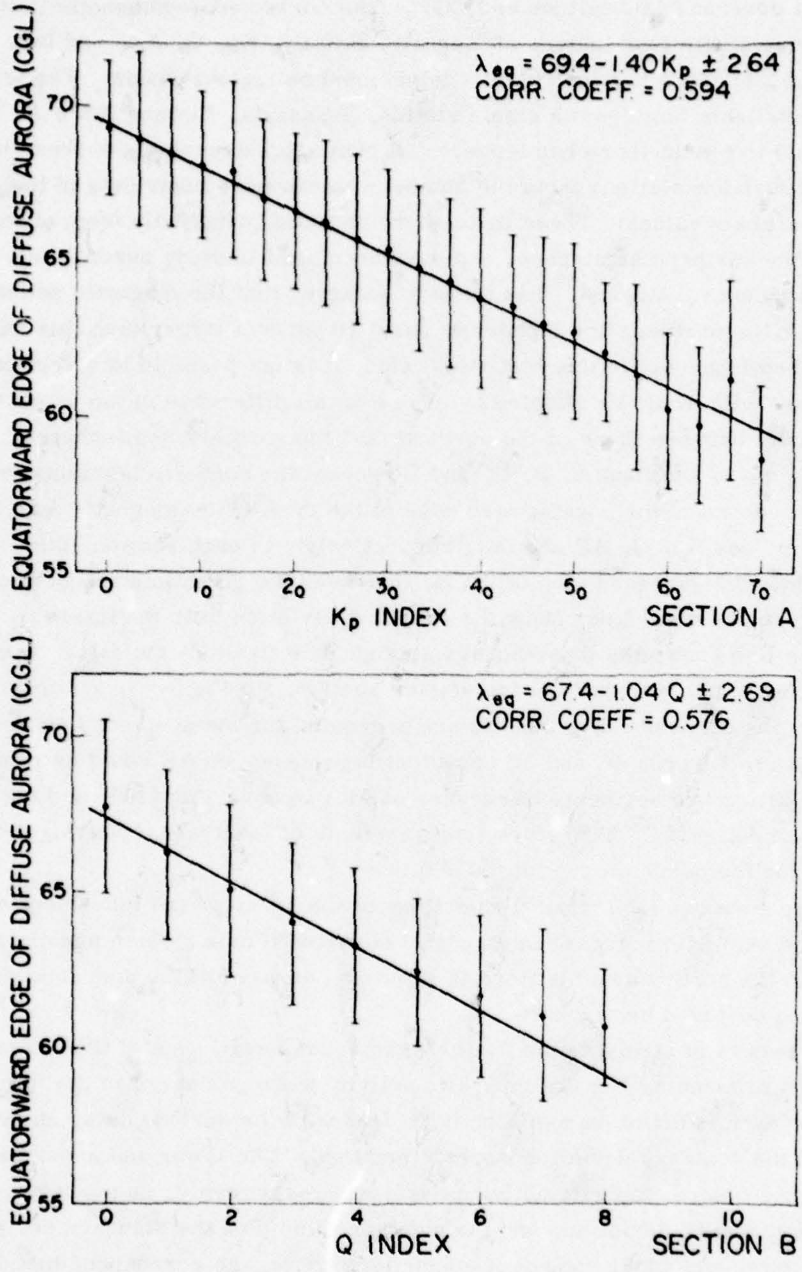
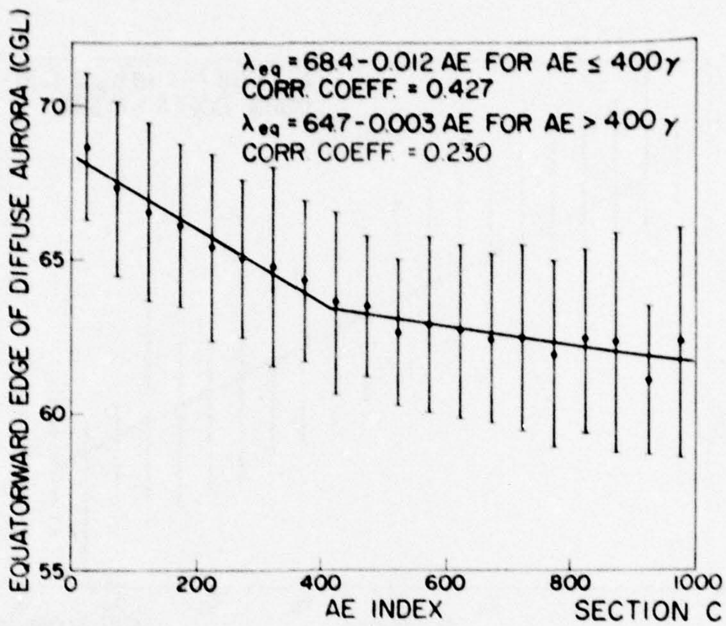
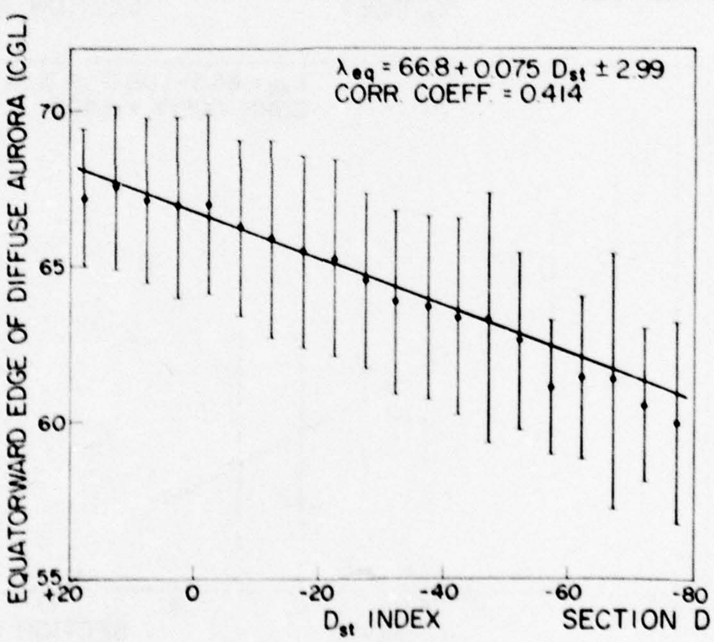


Figure 4. Least-Square First Order Fit to the Equatorward Edge of Diffuse Aurora as a Function of the Level of Magnetic Activity for Data from the Northern Hemisphere. Sections A, B, C, D are for the indices of magnetic activity Kp, Q, AE, and Dst. The term with ± sign in each equation is the standard deviation in the least-square first order fit.



λ_{eq} = 68.4-0.012 AE FOR AE ≤ 400γ
CORR. COEFF. = 0.427
λ_{eq} = 64.7-0.003 AE FOR AE > 400γ
CORR. COEFF. = 0.230
EQUATORWARD EDGE OF DIFFUSE AURORA (CGL)
70
65
60
55
0
200
400
600
800
1000
AE INDEX
SECTION C



λ_{eq} = 66.8+0.075 D_{st} ± 2.99
CORR. COEFF. = 0.414
EQUATORWARD EDGE OF DIFFUSE AURORA (CGL)
70
65
60
55
+20
0
-20
-40
-60
-80
D_{st} INDEX
SECTION D

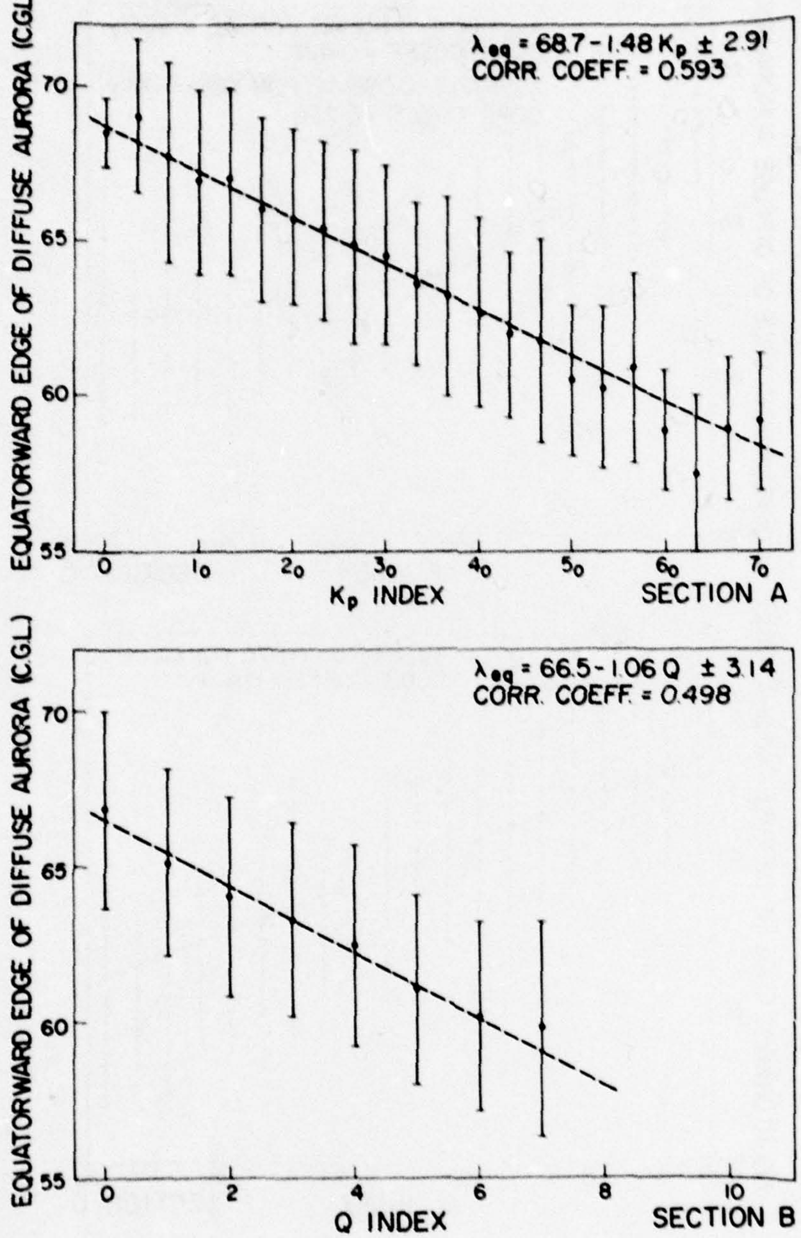
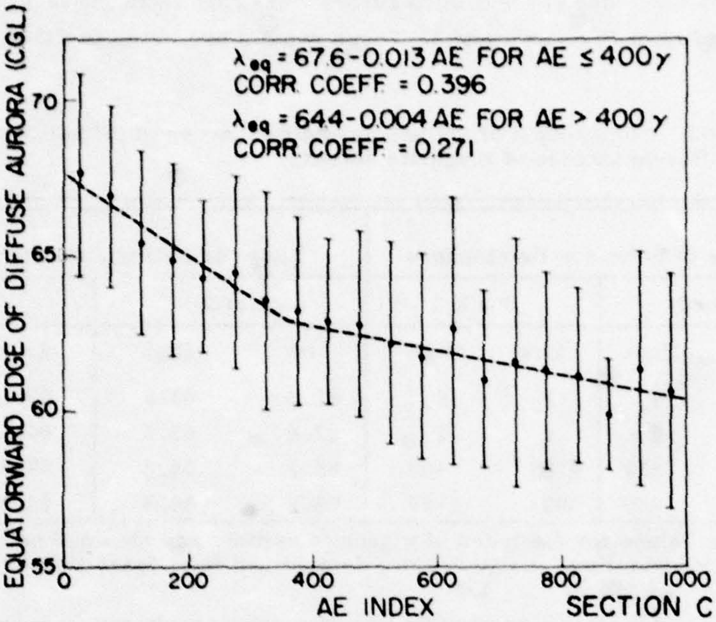
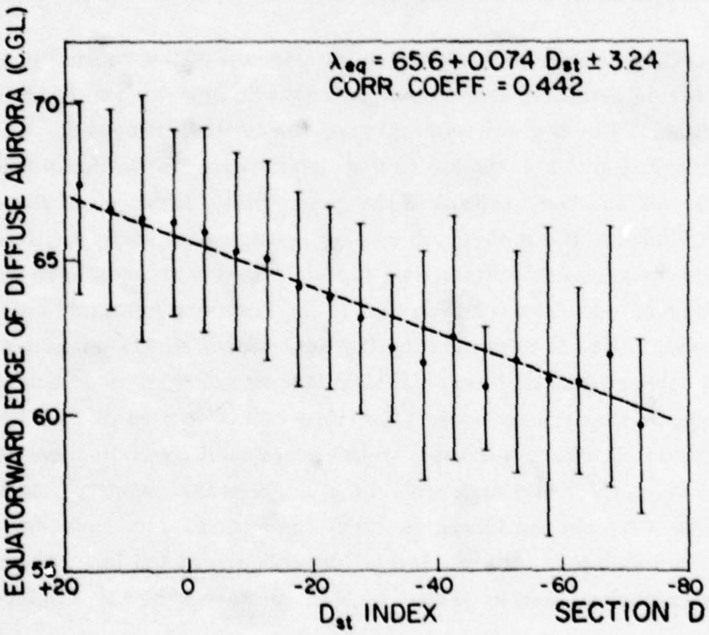


Figure 5. Similar to Figure 4. for Data from the Southern Hemisphere



λeq = 67.6-0.013 AE FOR AE ≤ 400γ
CORR. COEFF. = 0.396
λeq = 64.4-0.004 AE FOR AE > 400γ
CORR. COEFF. = 0.271
EQUATORWARD EDGE OF DIFFUSE AURORA (CGL)
AE INDEX
SECTION C



λeq = 65.6 + 0.074 Dst ± 3.24
CORR. COEFF. = 0.442
EQUATORWARD EDGE OF DIFFUSE AURORA (CGL)
Dst INDEX
SECTION D

of the equatorward edge of the diffuse aurora were read from the least-square straight-line fits of Figures 4 and 5. These results are listed in Table 3.

Table 3. Comparison of the geomagnetic latitudes of diffuse aurora for different indices of magnetic activity

Range of Index for Hemisphere					Range of Latitude for Hemisphere			
Index	North		South		North		South	
Index	Low	High	Low	High	Low	High	Low	High
Kp	1_+	4_o	2_-	4_+	67.5	63.8	66.2	62.3
Q	0	2	0	2	67.4	65.3	66.5	64.4
AE	25	350	25	400	68.1	64.2	67.3	62.8
Dst	2	-30	2	-30	66.9	64.5	65.8	63.8

Low and high values for the index of magnetic activity are obtained as mean value ∓ one standard deviation. Latitudes are determined from least-square straight lines in Figures 4 and 5.

In the above, an effort is made to use 68 percent of the central observations (average $\pm\sigma$) for determining the ranges of magnetic activity and the corresponding ranges of latitude. For a given hemisphere, the latitude ranges for different in indices show variation. This is due to the differences: (a) in the definitions of the indices Kp, Q, AE and Dst, and (b) in the geomagnetic latitudes of the observatories which contribute to the measurements of the magnetic activity. In addition to the differences for a given hemisphere, the boundary in the southern hemisphere is about one degree equatorward than that in the northern hemisphere.

Another possibility is to determine the dependence of CG latitude of diffuse aurora on the strength of the Interplanetary Magnetic Field. Our limited unpublished study shows that the southward Bz (Bz-) component exhibits a better control on the CG latitude of diffuse aurora than the northward Bz component (Bz+). Perreault and Akasofu[61] and Akasofu[62] have derived the quantity "magnetospheric flux" similar to AE from the Interplanetary Magnetic Field measurements. Under the present circumstances, the statistical dependence of CG latitude of diffuse aurora is better represented by Q than by AE, as seen above in Figures 4 and 5.

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61. Perrault, P., and Akasofu, S.-I., (1978) A study of geomagnetic storms, Geophys. J. R. Astr. Soc. 54:547.

62. Akasofu, S.-I., (1978) Interplanetary energy flux associated with magnetospheric substorms, EOS (Trans. AGU) 59:1167.

Stringer and Belon[51, 52] observed an equatorward movement of the aurora with increasing Kp index. Chubb and Hicks,[63] observing Hydrogen Lyman emission of the aurora from the OGO-4 satellite, noted that both midday and midnight auroras move about 6° equatorwards when the Kp index increases from 1 to 5. Deehr et al[64] observed auroral N_2^+ emissions from the OGO-5 satellite. They observed an equatorward movement of the aurora of 5.5° with the Kp index increasing from 0 to 4_-. They also noted that the plasmapause locations observed by Chapell et al[65] from OGO-5, follow similar variation w Kp index and are co-located a few degrees equatorwards of the N_2^+ emissions. Our observations of the equatorward edge of the diffuse aurora with Kp index are in agreement with those of the plasmapause by Chapell et al.[65] The movement of the equatorward edge of the oval in the present study is also in agreement with the previous observations.

As seen from Figures 4 and 5, amongst the indices Kp, Q, AE, and Dst for the level of magnetic activity, the first two indices show a better definition of the latitude of the diffuse aurora. In the present study, the Kp index yields better correction with latitude than that with the Q index. As the Q index is determined from the high-latitude auroral zone observatories, one would expect the Q index to be better than the Kp index; in fact, if Q was available like Kp on a planetary scale, the results for the Q index would be better than those for the Kp index. The evidence for such presumption is presented in the following.

The data of the northern hemisphere (which contains the magnetic observatory Sodankyla) were divided in 15° intervals of longitude. To the data in each longitude interval, a least-square straight-line fit was determined between the latitude of the aurora and the value of the Q index. A standard deviation was also computed from each fit. The standard deviation vs. longitude interval is plotted in Figure 6. The longitude of the station Sodankyla is also shown in Figure 6. It is seen that, in general, the standard deviation in the straight-line fit increases as the longitude difference of observations from the station Sodankyla increases. Also, in the southern hemisphere for the same longitude, the error in latitude is about twice as large compared to that in the northern hemisphere; thus, the dependence between the CG latitude and the Q index would have a smaller error compared to that for the fit with other indices of magnetic activity, provided Q

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63. Chubb, T.A., and Hicks, G. T., (1970) Observations of the aurora in the far ultraviolet from OGO-4, J. Geophys. Res. 75:1290.

64. Deehr, C.S., Sten, T.A., Egeland, A., and Omholt, A., (1970) Relation of electron and proton aurora to geomagnetic activity, Physica Norvegica 4:95.

65. Chapell, C.R., Harris, K.K., and Sharp, R.W., (1970) A study of the influence of magnetic activity on the location of the plasmapause as measured by OGO-5, J. Geophys. Res. 75:50.

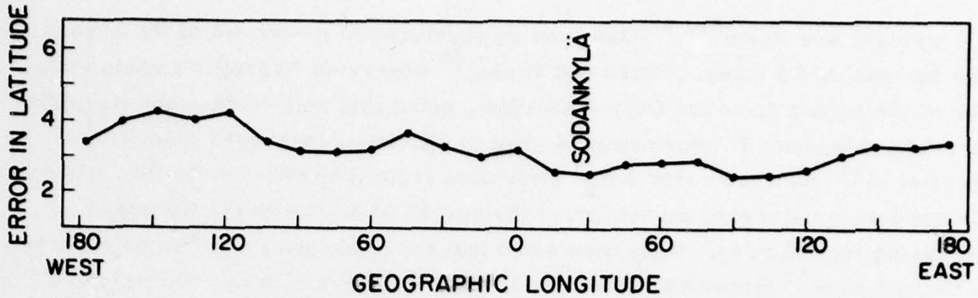

Figure 6. Magnitude of Standard Deviation vs. Geographic Longitude

index values were available on a planetary scale, similar to those for the indices Kp, AE, and Dst.

9. DEPENDENCE OF THE OVAL ON THE CGT

Starkov[66] used the geometrical shape of a circle for representing the auroral ovals. Holzworth and Meng[67] found that in a mathematical formulation the auroral data of Feldstein[68] is best represented by the shape of a circle; therefore, an empirical relation for a least-square circle was fitted to the data of each hemisphere in the present study. The parameters used in the circle fit are the CG latitude of the equatorward edge of the diffuse aurora, the CG time, and the level of magnetic activity at the time of observation. As the use of the Kp and Q indices shows better correlation (Figures 4 and 5) than the use of AE and Dst indices, only the former are used in this study. The empirical equations are summarized in Table 4. The first three columns present the index of magnetic activity, the hemisphere, and the number of observations, respectively. The next column presents the equation for the least-square circle fit. It is followed by the coefficient of correlation. The last column provides the reference. The upper half of the table presents the results from this study and the lower half presents the results by other workers.

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66. Starkov, G.V., (1969) Analytical representation of the equatorial boundary of the oval auroral zone, Geomagn. Aeron. (Eng. ed.) 9:614.
67. Holzworth, R. H., and Meng, C.-I., (1975) Mathematical representation of the auroral oval, Geophys. Res. Lett. 2:377.
68. Feldstein, Y.I., (1963) On morphology of auroral and magnetic disturbances at high latitudes, Geomagn. Aeron. (Eng. ed.) 3:183.

Table 4. Summary of the least-square circle fit to the equatorward edge of diffuse aurora

INDEX OF MAGNETIC ACTIVITY	HEMI-SPHERE	NUMBER OF OBSERVATIONS	EMPIRICAL EQUATION	CORR. COEFF.	REMARKS
Kp	N	5683	$\theta_{eq} = 18.76 + 1.39\ Kp + 2.68 \cos(t-13)$	0.650	
Kp	S	2701	$\theta_{eq} = 19.45 + 1.48\ Kp + 2.79 \cos(t-26)$	0.676	
Q	N	5683	$\theta_{eq} = 20.85 + 1.01\ Q + 2.55 \cos(t-9)$	0.623	
Q	S	2701	$\theta_{eq} = 21.4 + 1.11\ Q + 3.09 \cos(t-27)$	0.615	
Q	N		$\theta_{eq} = 18 + 0.9\ Q + 5.1 \cos(t-12)$		Starkov[66]
Kp	N		$\theta_{eq} = 19.2 + 0.35\ Kp + 0.17\ (Kp)^2 + \{1.3 + 2.56\ Kp - .34(Kp)^2\} * \cos(MLT)$		Galperin et al[69]
$a_p(Kp)$	S		$\theta_{eq} = \{3.0078 + 0.0455\ \phi + 12.9 \sin(0.364\ \phi + 71.162)\} + \{1.0018 + 0.01305\ \phi + 2.550 \sin(0.629\ \phi + 69.190)\} * 10^{-2}\ a_p\ (Kp)$		Thomas and Bond[70]

Each equation has three terms. The first term is an empirical constant and presents the radius of the circle in colatitude. The second term depends on the index of magnetic activity. The coefficient of the index of magnetic activity presents the expansion or reduction in the length of the radius (degrees of colatitude) which provides the size of the oval. In the last term, the trigonometric function has the time dependent part "t." The phase shift gives the azimuth (measured in degrees from the midnight meridian towards the morning sector as positive), and the coefficient presents the colatitude offset of the center of the circle from the CG pole. For a given index of magnetic activity, the circle in the northern hemisphere differs from the circle in the southern hemisphere both in the length of the radius as well as the location of the center of this empirical circle. This could be due to the asymmetry or the lack of conjugacy of the auroral activity between the northern and southern hemispheres. This result was seen in Figures 4 and 5 for latitude dependence of the diffuse aurora on the magnetic activity indices Kp, Q, AE, and Dst.

In Table 4, the radius of the Starkov[66] circle is based on the data from the northern hemisphere. The data are from the ground-based observations and refer predominantly to discrete auroral arcs. The comparison of Starkov's[66] equation with the corresponding equation (Number 3) shows that, in the present study, the radius of the diffuse auroral oval is larger and the center of the circle is closer to the CG pole, than that of Starkov.[66] This is consistent with the observation that, in the night sector, the boundary of the diffuse aurora lies equatorward, or coincides with that of discrete aurora. The comparison of the trigonometric terms shows that the equatorward edge of diffuse aurora is more stable; that is, it has less variation in CG time dependence, $2 \times 2.6^\circ$ for diffuse aurora, vs $2 \times 5.1^\circ$ for discrete aurora.

Galperin et al[69] derived their empirical equation for the equatorward edge of the diffuse aurora from the measurements made by the Aureole 1 and 2 satellites. Their results are quadratic in Kp index. These are in agreement with the linear equations obtained in the present study.

Thomas and Bond[70] derived their equation from auroras of ASCA (all-sky camera) data. The detectability threshold of the DMSP system is better than that of an ASCA system. Their results refer basically to discrete auroras; therefore,

69. Galperin, Yu. I., Crasnier, J., Lisokov, Yu. V., Nikolaenko, L. M., Sinitsyn, V. M., Sauvand, J. A., and Khalipov, V. L., (1977) The diffuse aurora. I. A model for the equatorial boundary of the diffuse surge zone of auroral electrons in the evening and midnight sectors, Trans. from Kosmicheskie Issledovania **15030**:421.
70. Thomas, I. L., and Bond, E. R., (1977) An empirical equation for the austral auroral oval, Geophys. Res. Lett. **4**:411.

the radius of these ovals is smaller than the radius of the diffuse aurora of the present study.

To study the asymmetry of the auroral ovals of the northern and southern hemispheres, data from each hemisphere are divided into groups according to the intervals of the Q index. A least-square circle was fitted to all the data of a given Q index. The empirical relations showed variability similar to that in Table 4. From these relations, a radius for each value of the Q index was available. A least-square straight-line was fitted between the radius and the Q index by weighting each value of the radius with the corresponding number of observations contributing to the radius. The least-square straight-line fits for the northern and the southern hemisphere are shown in Figure 7. The top section shows the results for the northern hemisphere, and the bottom section shows the results for the southern hemisphere. The number of observations available for each value of the Q index are shown at the top of each figure, along with the empirical equation for the straight-line fit. The comparison of constant terms shows that the radius of the southern oval is about 1° larger than that of the northern oval for quiet magnetic conditions ($Q=0$). The reason for the difference in the sizes of the northern and southern ovals is not yet understood.

In Figure 7, only the radius of the least-square circles for different values of Q index was used. The systematic change in the ovals with the variation of Q index is shown in Figure 8. For the purpose of presentation, the data for a given Q value are divided in hourly intervals of CG time. Over each hourly interval, an average value, and the standard deviation of the latitude of the diffuse aurora are determined. These are shown in Figure 8. The left-hand side of the figure presents the results for the data of the northern hemisphere and the right-hand side of the figure shows the results for the southern hemisphere. There are five blocks on each side. These are for the Q indices 0-4 (from top to bottom). In each block, the full circles show the average hourly value of latitude. The vertical lines show the standard deviation ($\pm\sigma$) of the mean. The curve (continuous for northern hemisphere and dashed for the southern hemisphere) shows the least-square circle fit. The latitude scales are shown alternately on the left and right sides of the blocks. For reference, a 66° latitude line is shown in each block. The equation for the curve, the least-square circle fit, is shown at the top of each block. In a given hemisphere, the size of the oval increases equatorwards with increasing Q; that is, the latitude position moves equatorwards from the top block to the bottom block. A look at the equations shows that the center of the empirical circle also changes (the coefficient and the phase in the cosine term) with change in Q. The comparison of northern and southern ovals for the same Q (blocks in a row) shows that the southern oval is about a degree equatorward with respect to the northern

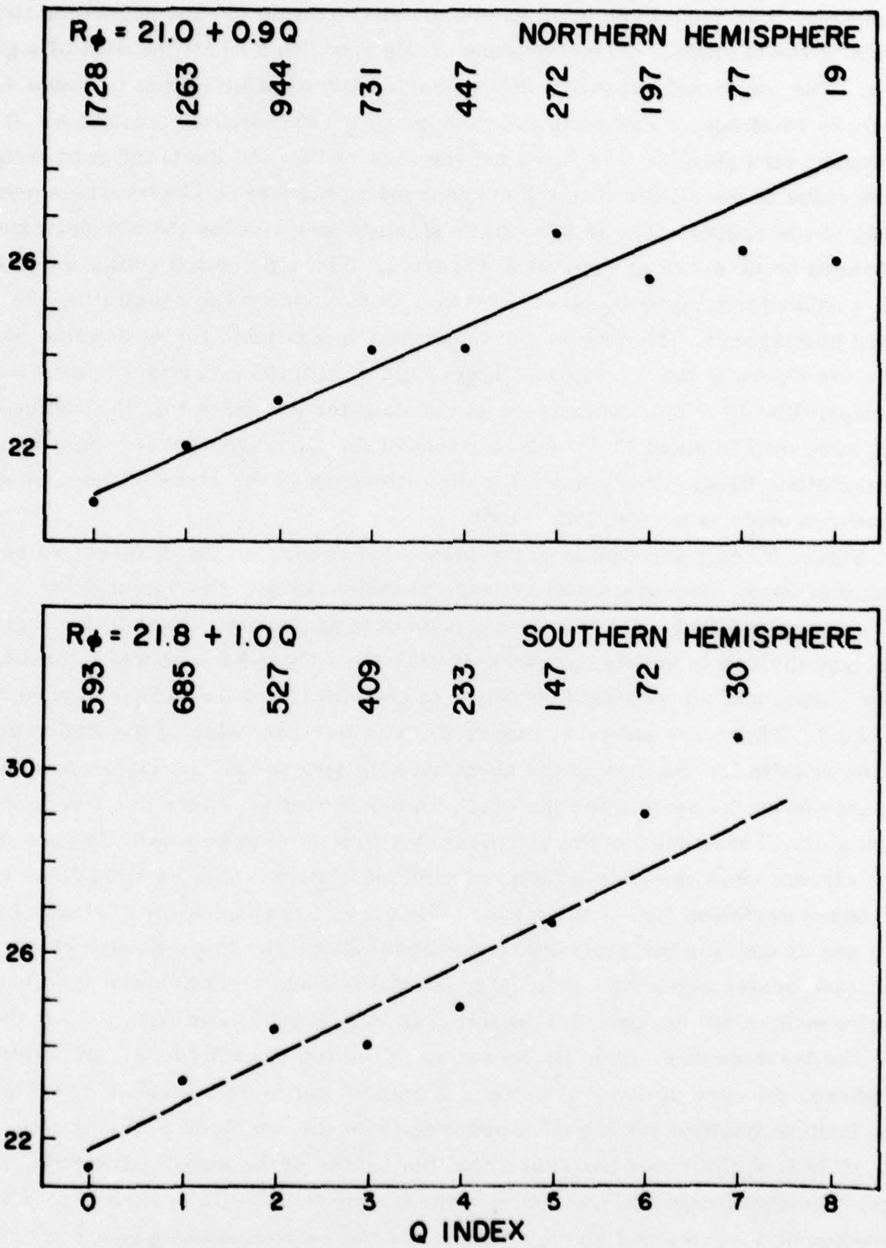


Figure 7. Relation Between the Size of the Diffuse Auroral Oval and the Index of Magnetic Activity Q. Values for radius are from Table 4.

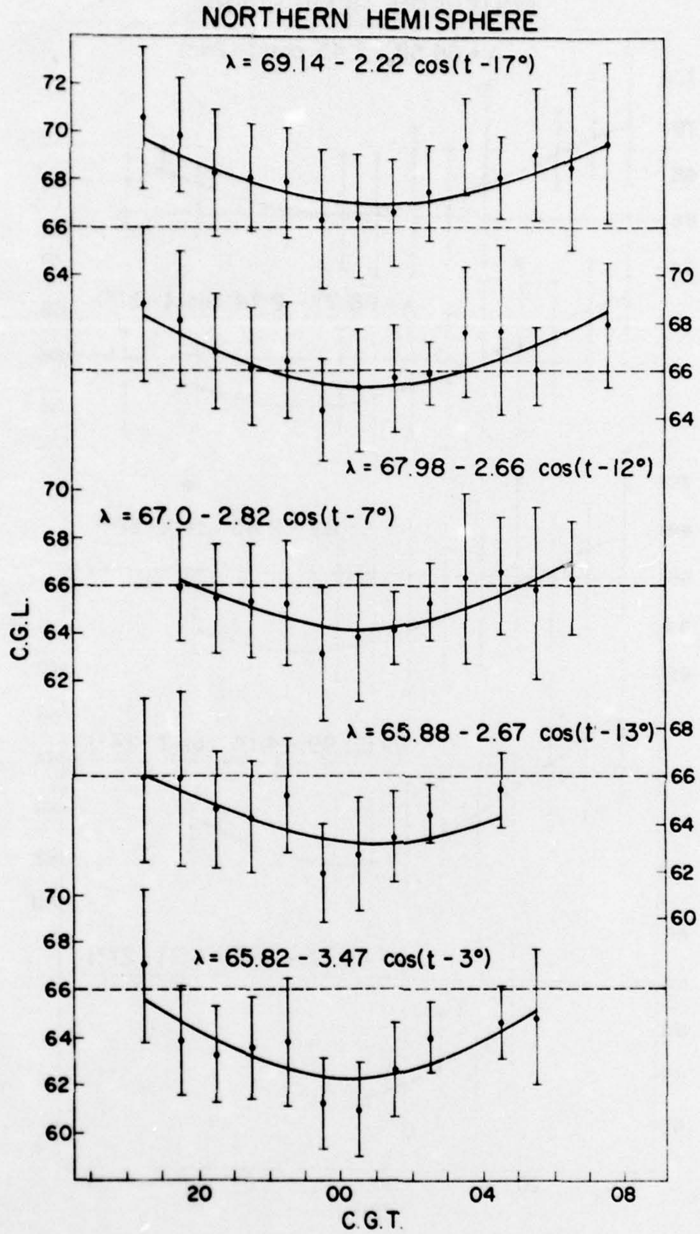
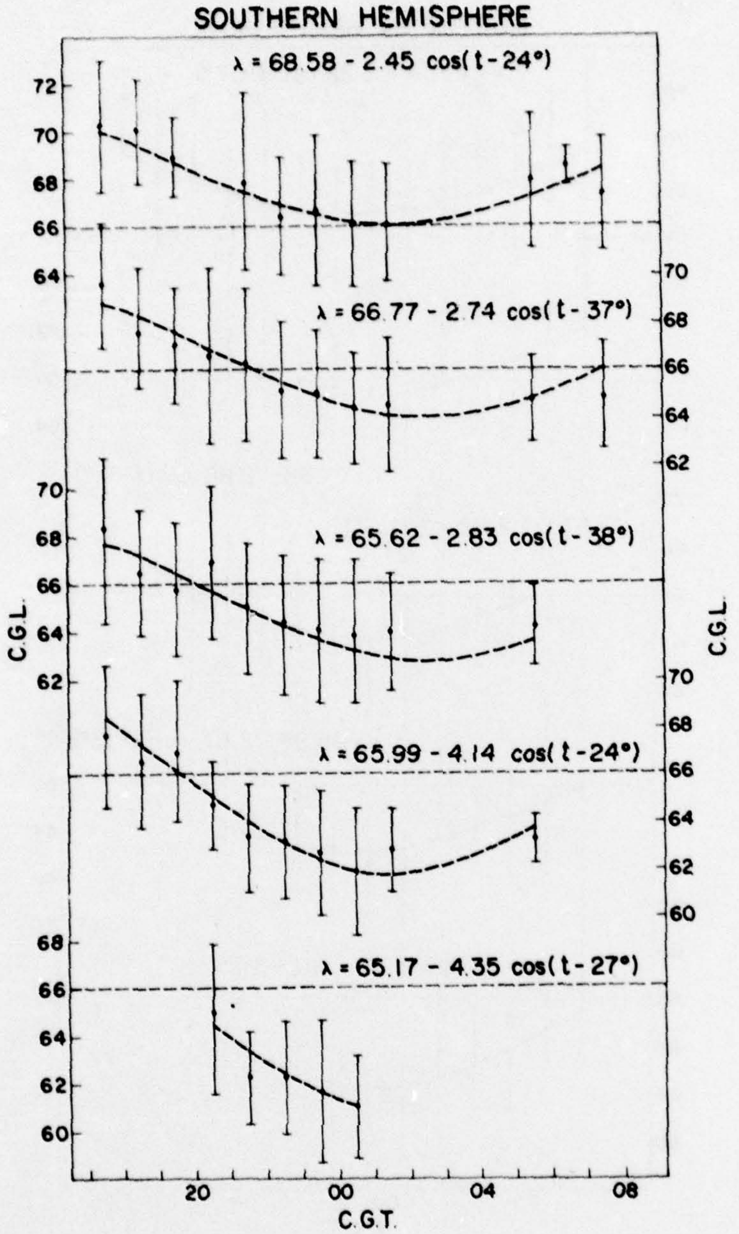


Figure 8. Dependence of the Corrected Geomagnetic Latitude (CGL) of the Equator Equatorward Edge of Diffuse Aurora on Corrected Geomagnetic Time (CGT) for Various Values of the Q Index


SOUTHERN HEMISPHERE
λ = 68.58 - 2.45 cos(t-24°)
λ = 66.77 - 2.74 cos(t-37°)
λ = 65.62 - 2.83 cos(t-38°)
λ = 65.99 - 4.14 cos(t-24°)
λ = 65.17 - 4.35 cos(t-27°)
C.G.L.
C.G.L.
20
00
04
08
C.G.T.

oval. Also this difference, or asymmetry, increases with increasing value of Q. The asymmetry is due to both the change in the radius, or the constant part, and the displacement of the respective centers of the circles.

Another useful presentation of the equatorward edge of the diffuse aurora with respect to the Q index is shown in Figures 9 a-e. Feldstein and Starkov[48] have presented the data of the discrete auroral arcs in the forms of auroral ovals for various levels of the Q index of magnetic activity. Whalen[71] combined these data with the oval plotter and nomograph which could be superposed on the geographic map of the earth. The diffuse auroral circles from the northern and southern hemispheres, in magnetic coordinates determined for the various values of the Q index in this study (from equations in Figure 8), are shown along with the Feldstein ovals for discrete auroral arcs. It is noted that these empirical circles of diffuse aurora lie equatorwards of the discrete auroral ovals. This is consistent with the observation by Sandford and others[14] that equatorward boundary of diffuse aurora coincides or lies equatorwards of the discrete aurora. It is noted that for a given value of Q, the diffuse auroral edge in the southern hemisphere (dashed curves in Figure 9) lies equatorwards of that (continuous curve) in the northern hemisphere.

10. CONCLUSION

The size of the auroral oval has been presented in terms of the CG latitude dependence of the equatorward edge of the diffuse aurora on the level of magnetic activity. Due to lack of data in the day sector, the conclusions refer only to the evening, night, and morning sectors of the ovals. The peak in the distribution of observations of the diffuse auroras, in the midnight hours (CGT), is due mainly to the observational limitation of the optical instruments aboard the satellites. The data in this study are not conclusive in regard to the longitudinal dependence of the diffuse aurora. In the night sector, the equatorward edge of the diffuse aurora averages to 63°-64° CGL. The latitude dependence of the equatorward edge of the oval does not exhibit any signif cant seasonal dependence. The most predominant factor controlling the latitude dependence of the equatorward edge of the diffuse aurora of the oval is the magnetic activity. Empirical relations are derived between indices of magnetic activity and the latitudinal boundary of the diffuse aurora in this study for monitoring the size and the location of the auroral

71. Whalen, J.A., (1970) Auroral Oval Plotter and Nomograph for Determining Corrected Geomagnetic Local Time, Latitude and Longitude for High Latitudes in the Northern Hemisphere, Environmental Research Papers, No. 327, AFCRL-70-0422. AD A713170

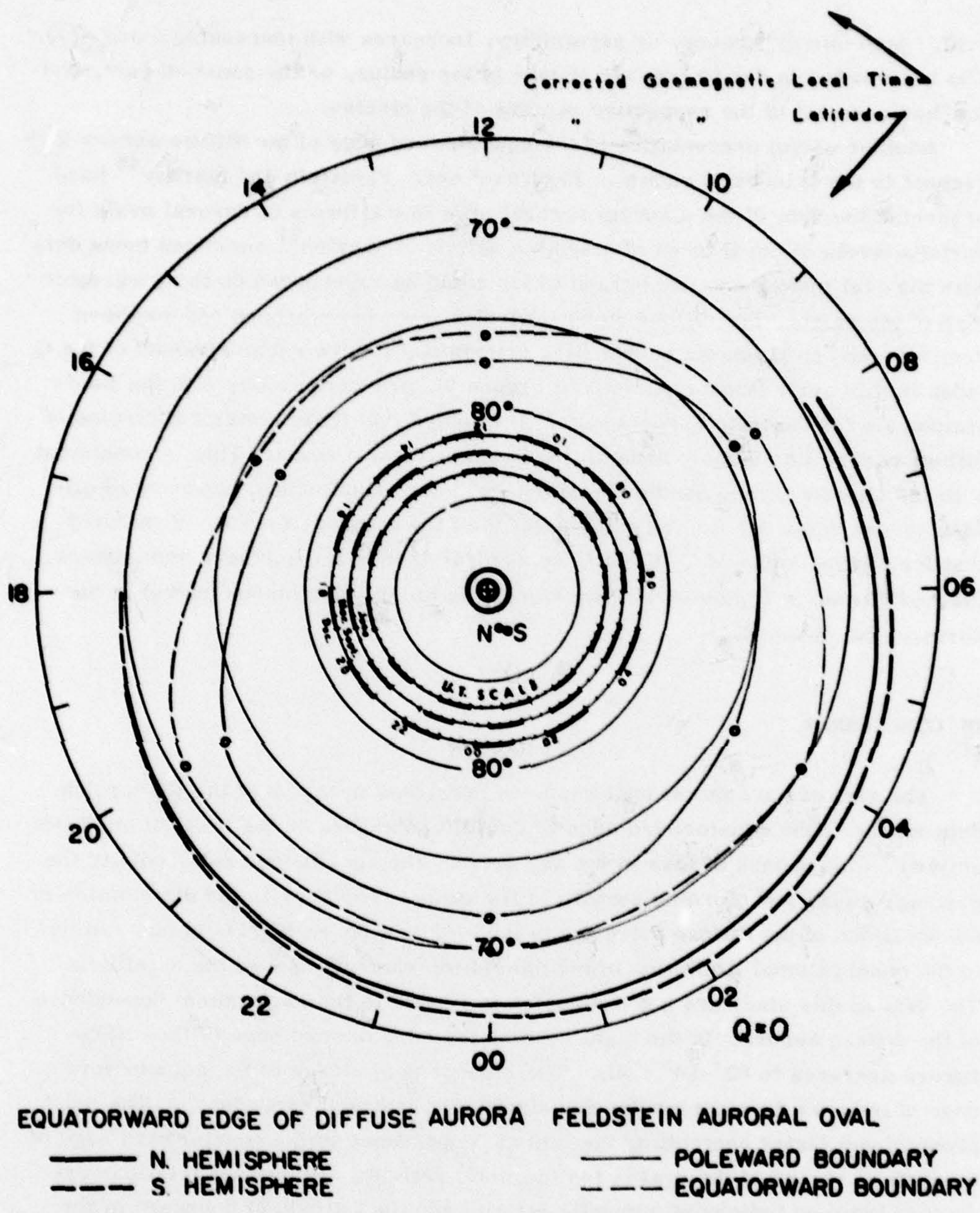
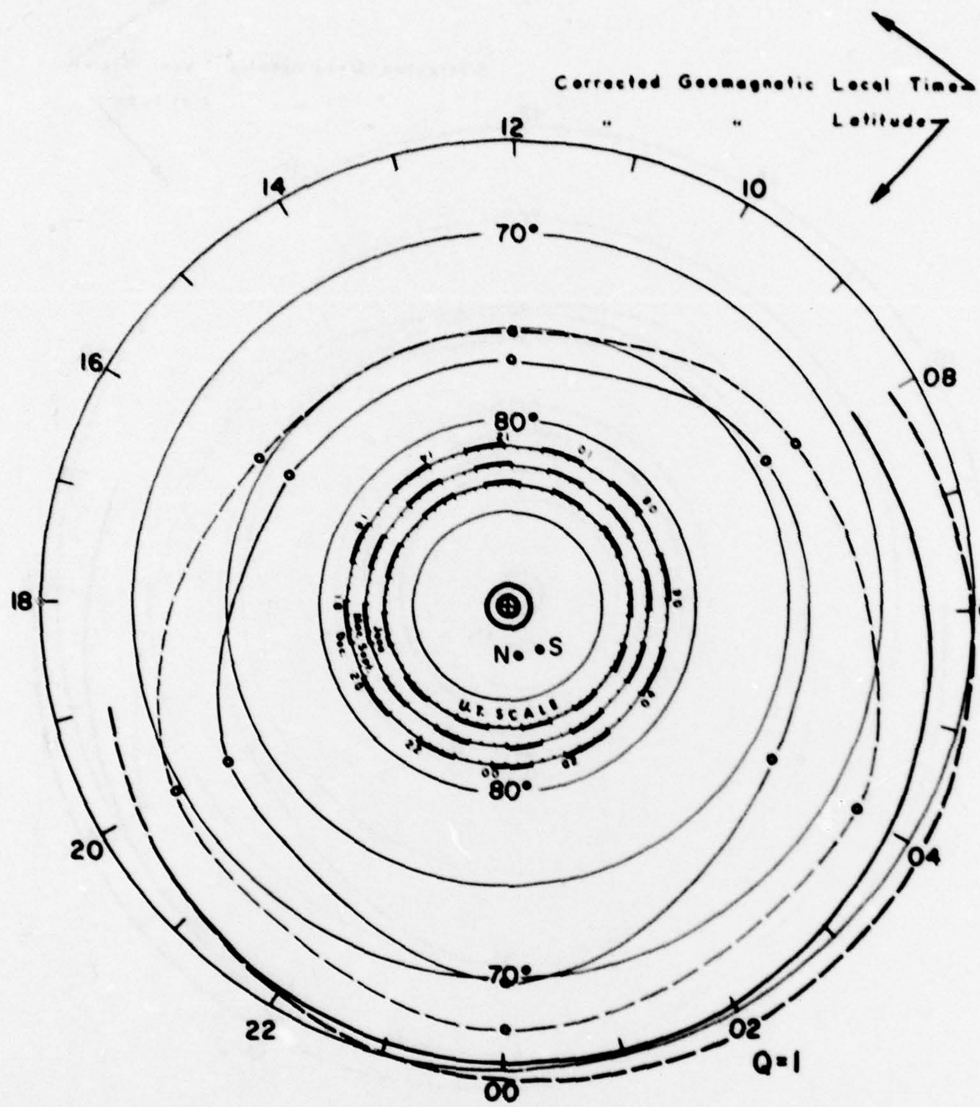
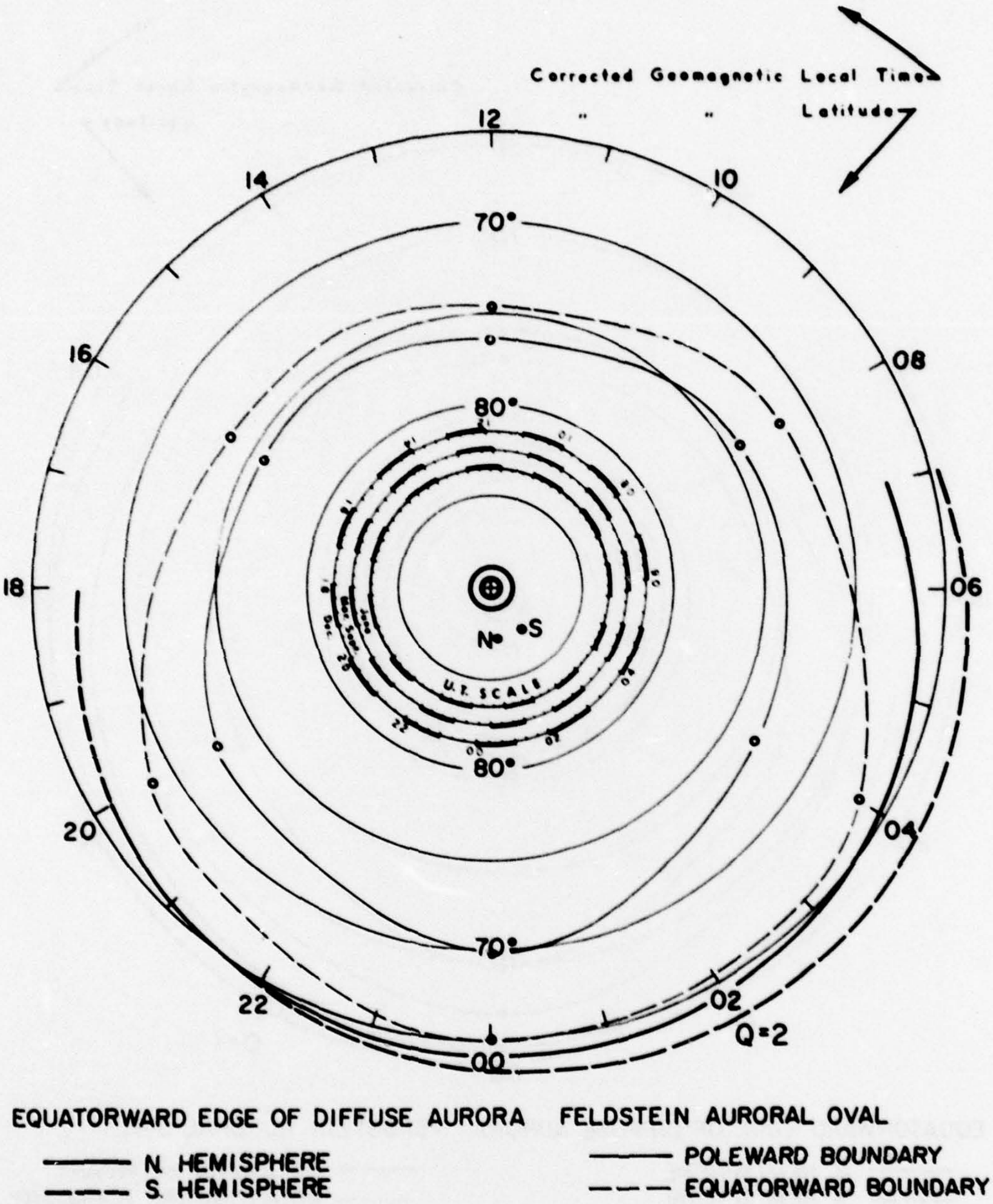


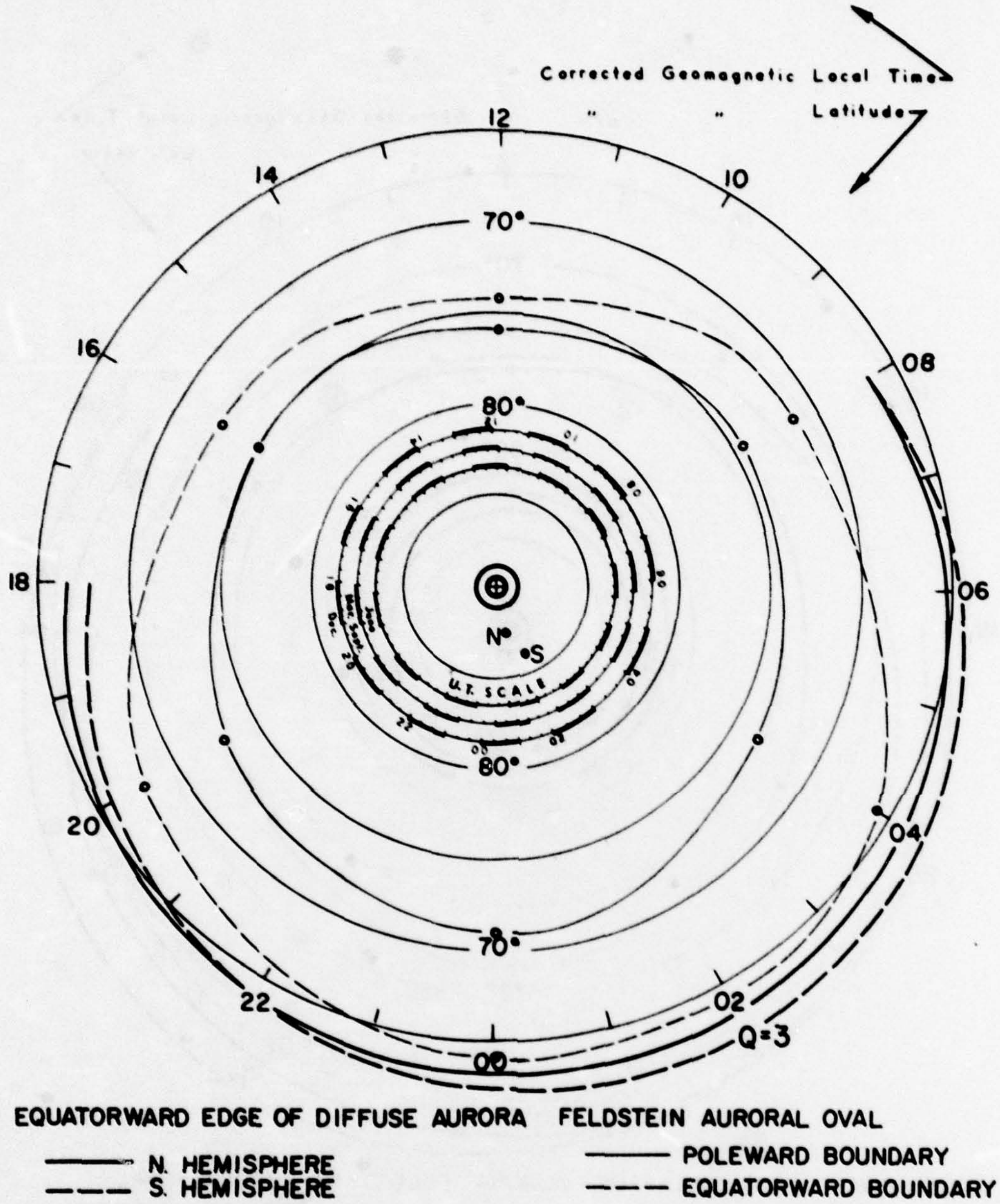
Figure 9a-e. Empirical Circles of Diffuse Aurora and Feldstein Ovals of Discrete Aurora for Various Values of Q Index



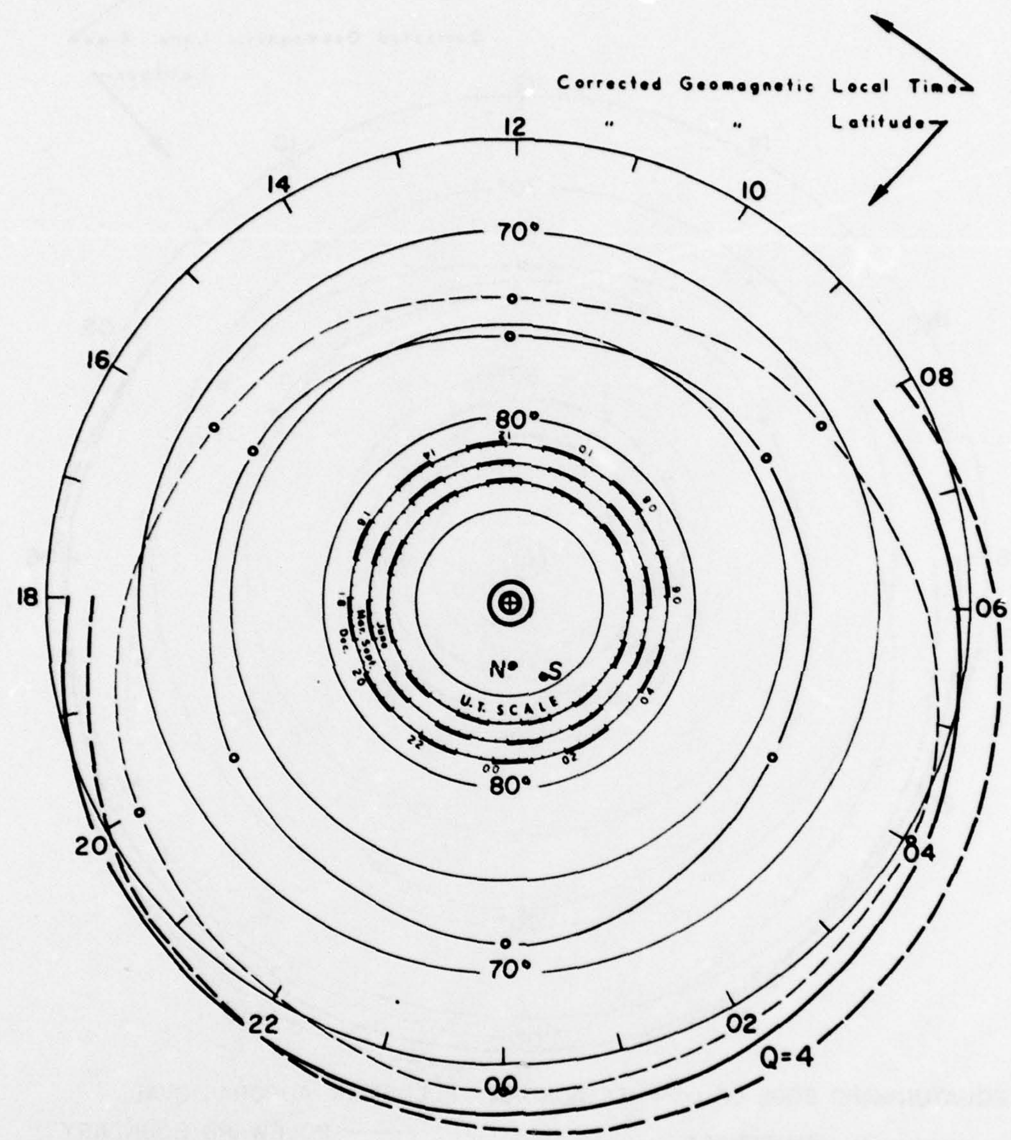
EQUATORWARD EDGE OF DIFFUSE AURORA
N. HEMISPHERE
S. HEMISPHERE

FELDSTEIN AURORAL OVAL
POLEWARD BOUNDARY
EQUATORWARD BOUNDARY


Corrected Geomagnetic Local Time
" " Latitude
12
14
10
70°
16
08
80°
18
06
N
S
U.T. SCALE
80°
20
04
70°
22
02
00
Q=2
EQUATORWARD EDGE OF DIFFUSE AURORA
N. HEMISPHERE
S. HEMISPHERE
FELDSTEIN AURORAL OVAL
POLEWARD BOUNDARY
EQUATORWARD BOUNDARY



Corrected Geomagnetic Local Time
"
"
Latitude
12
14
10
16
08
18
06
20
04
22
02
00
70°
80°
80°
70°
N
S
U.T. SCALE
Q=3
EQUATORWARD EDGE OF DIFFUSE AURORA
N. HEMISPHERE
S. HEMISPHERE
FELDSTEIN AURORAL OVAL
POLEWARD BOUNDARY
EQUATORWARD BOUNDARY



EQUATORWARD EDGE OF DIFFUSE AURORA

——— N. HEMISPHERE

– – – S. HEMISPHERE

FELDSTEIN AURORAL OVAL

——— POLEWARD BOUNDARY

- - - - EQUATORWARD BOUNDARY

oval. The Kp and Q indices show the best correlation with the latitude dependence of the diffuse aurora. The size and location of the oval show a dependence on both the level of magnetic activity and the CG time. Taking advantage of the fact that the auroral oval is reasonably circular in shape, the size of the oval is presented in terms of the radius and the location of the center of the auroral oval. Such an analysis is useful in modeling and predicting the location of the auroral oval. The empirical relations should be examined further for studying the dynamics of the oval with the changes in interplanetary magnetic field. It would also be useful to study the relationship between the precipitating particle flux at high latitudes, and the equatorward extent of the oval, for understanding the interactions between the magnetosphere and the ionosphere at high latitudes.

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16. Deehr, C.S., and Egeland, A., (1972) Auroral morphology, Ann. Geophys. 28:415.

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18. Eather, R.H., (1975) Advances in magnetospheric physics: aurora, Rev. Geophys. Space Phys. 13:925.

19. Hultqvist, B., (1974) Rocket and satellite observations of energetic particle precipitation in relation to optical aurora, Ann. Geophys. 30:223.

20. Frank, L.A., (1975) Magnetospheric and auroral plasmas: a short survey of progress, Rev. Geophys. Space Phys. 13:1974.

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